Energy Dependence of Proton Damage in Optical Emitters†

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Abstract *- The energy dependence of proton displacement damage effects is investigated for light-emitting diodes and laser diodes. Injection-enhanced annealing occurs more rapidly when devices are irradiated with protons below 50 MeV compared with annealing from 200 MeV protons. A different interpretation of damage in amphoterically doped LEDs is used to show that the dependence of damage on energy is relatively flat for energies above 50 MeV compared to older results in the literature.*

I. INTRODUCTION

Numerous investigations have been made to determine the energy dependence of proton displacement damage in III-V devices [1-6]. The results of these studies are somewhat inconsistent and contradictory. The main region where discrepancies have occurred is the energy range above 50 MeV where theoretical calculations of non-ionizing energy loss (NIEL) predict a plateau, followed by slight increases in effective damage per proton at higher energies. Experimental results for some devices -- particularly amphoterically doped LEDs -- show that the damage factor continues to decrease at high energies. Reed, et al. [6] found that damage in single-heterojunction LEDs exhibited the continued decrease in NIEL at high energies that was observed for amphoterically doped LEDs, but that double-heterojunction LEDs had a much flatter energy dependence. Less information is available about the energy dependence of damage in laser diodes. Lee, et al. concluded that damage in laser diodes increased at higher energies [5], in general agreement with theoretical calculations of NIEL However, that study was somewhat limited by the small sample size and reproducibility of their experiments. More work is needed to determine how damage in laser diodes depends on proton energy.

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This paper addresses energy dependence from a somewhat different standpoint. Although NIEL may be an excellent concept for calculating the total energy that goes into displacement processes, it does not include other factors that are important in the way that the damage affects devices, and hence the net change that is measured in a real device after irradiation. The most glaring omission from the NIEL concept is annealing, which can be very important for some types of III-V optical emitters. Dale, et al. discussed track structures in silicon from proton damage and showed that most of the energy goes into Frenkel pairs at low energy, whereas at energies above 50 MeV an increasing fraction of the interactions create isolated cluster defects [7]. Similar processes occur in III-V devices, but they have been studied in less detail. However, the microscopic nature of the damage is clearly different at low and high energies, which has to be taken into account when damage comparisons are made.

Four devices were selected for this study, as shown in Table 1. They include two types of LEDs along with two types of laser diodes. The Lumex laser is a strained quantum-well laser, designed for high efficiency and low threshold current.

Device	Manuf.	Wavelength (nm)	Function
OP130	Optek	930	LED
OD800	Optodiode	820	LED
LDP65001	Lumex	650	Laser
SV5637	Honeywell	850	VCSEL

In order to make meaningful comparisons of damage, parameters must be selected which depend on displacement damage in a predictable manner [8-11]. For laser diodes, threshold current has been found to increase linearly with proton fluence [12], and this also appears to be true for VCSELs [13]. LED parameters are less straightforward. Earlier work by Rose and Barnes showed that optical power output of older types of LEDs exhibited a superlinear dependence on fluence when the light output was measured at constant forward injection; their data obeyed a 2/3 power law that was consistent with a lifetime damage model [8]. Later work showed that optical power output of newer

LEDs made with double heterojunctions did not follow the 2/3 power dependence, but had a slope that was nearly one [11]. One possible reason is the complicated operation of double-heterojunction devices, which are not necessarily limited by lifetime damage.

Another key factor in evaluating damage is annealing. In contrast to neutron damage, proton displacement damage is generally stable for *unbiased* devices at temperatures below 200 °C [14]. However, many optical emitters are strongly sensitive to recombination-enhanced annealing [15]. Annealing experiments were done on the devices in this study to characterize the dependence of annealing as well as to determine how measurements of key device parameters, which cause some of the damage to anneal, affect the results and the interpretation of displacement damage. This can be an important interference in studies of this type.

II. Experimental Approach

Proton tests were done at two facilities. The University of California Davis cyclotron was used for irradiations at 25 and 50 MeV. Irradiations at higher energies were done at Indiana University. All devices were irradiated without bias (all pins grounded during irradiation).

Groups of 100 or more devices of each type were purchased, and all devices within each group were subjected to electrical and optical tests in order to assure that the devices selected for the energy study were representative of the device population. Subgroups of 6-10 parts of each type were then irradiated at four different energies. The fluence was selected to get nearly the same amount of damage during each run, using older experimental information to estimate the fluence.

Electrical measurements were done before and after each irradiation using an Agilent Technologies 4156 parameter analyzer and a silicon photodiode. A thermoelectric cooler was used to set the device temperature to 25± 0.1 °C during measurements.

After initial evaluations were completed, some devices were used for annealing studies by operating them at constant bias for various time intervals, measuring the light output and electrical characteristics after each bias sequence.

III. Results

A. Energy Dependence

OP130 Amphoterically Doped LED

The energy dependence of the OP130 was done with fluences that decreased the light output to about 35% of the initial light output. Slightly more damage occurred at 200 MeV, and that result was compared with results at the other fluences by normalizing the damage using two different models for light output degradation: n = 2/3, and n = 1. The results are shown in Figure 1. Error bars show the standard deviation for six devices at each energy.

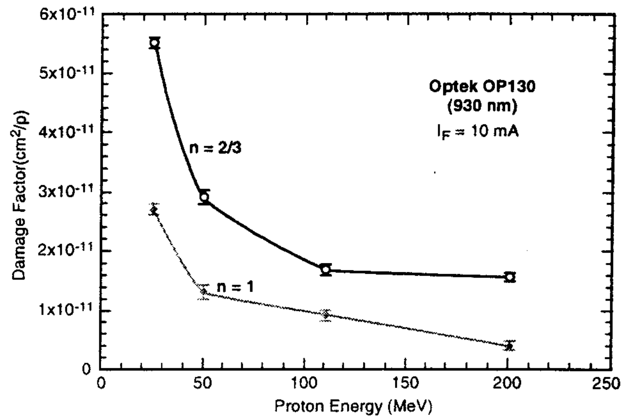

Figure 1. Energy dependence of damage in the OP130 amphoterically doped LED.

The 2/3 power dependence for light intensity is based on lifetime damage at constant injection [8], and fits experimental observations of optical power degradation [8,11]. Our results suggest that using that value for n (based on optical output power measurements) flattens the dependence of the damage factor at high energies compared to results that were based on measurements of minority carrier lifetime by Barry, et al.[4], resulting in an energy dependence for amphoterically doped LEDs that is very nearly the same as that for double-heterojunction LEDs. Note also that our measurements correspond to operation at 10% of maximum operating current, while the work of Barry et al. was done at currents that were a factor of ten lower, below the usual region of useful operation for those devices.

OD800 Double-Heterojunction LED

The energy dependence of damage in the OD800 LED is shown in Figure 2. The OD800 uses a double-heterojunction structure, and has the same maximum operating current as the amphoterically doped OP130, 100 mA. The energy dependence that we measure is similar to the results reported by Reed, et al. for a different type of double-heterojunction LED [6]. They used somewhat lower operating currents in their study.

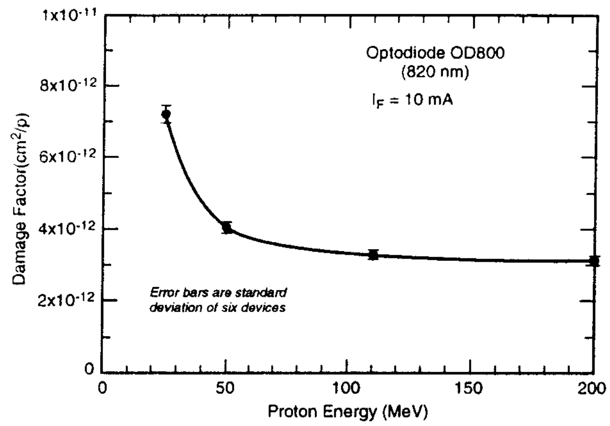

Figure 2. Energy dependence of the damage factor of the OD800 double-heterojunction LEDs.

The nearly flat dependence of damage factor at high energies has been observed for most advanced LEDs that are made with heterojunctions. Note also that unlike amphoterically doped LEDs, heterojunction LEDs are relatively unaffected by injection-enhanced annealing.

Lumex Laser Diode

The energy dependence of damage in the Lumex laser diodes (650 nm) are compared with the energy dependence of 780 nm laser diodes observed by Lee, et al. [5] in Figure 3. Our results are somewhat different, showing an energy dependence that is very similar to that observed for double-heterojunction LEDs - essentially flat at energies above 100 MeV - - instead of the increase reported in the earlier work. The larger sample size used in our experiments provides more consistent results than those used in the earlier study. We also carefully controlled measurement conditions to limit interference from injection-enhanced annealing, which can be of considerable importance in these structures.

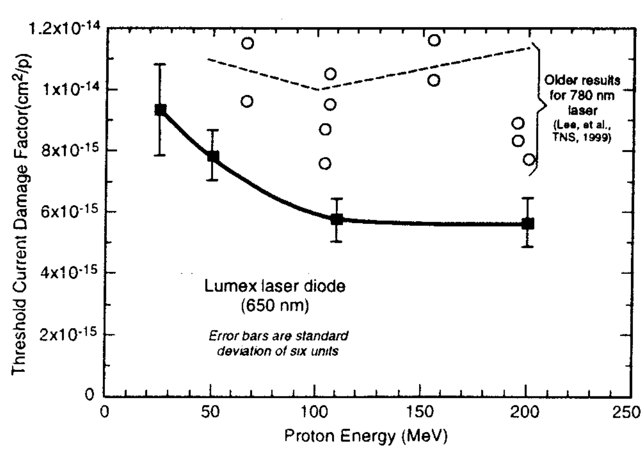

Figure 3. Energy dependence of threshold current damage factor of the Lumex 650 nm laser diode.

Damage in different samples of the laser diodes was less consistent than damage in the LEDs in our study, which is the reason for the somewhat larger error bars in the results shown in Figure 3. The energy dependence of the laser diodes appears to be very similar to the energy dependence of double-heterojunction LEDs, and is considerably different from the conclusions reached by Lee, et al. in their earlier study.

Honeywell VSCEL

Energy dependence of damage in the VCSEL devices is shown in Figure 4. The results are similar to those observed for the Lumex laser diode, but appear to show a sharper energy dependence between 50 and 100 MeV.

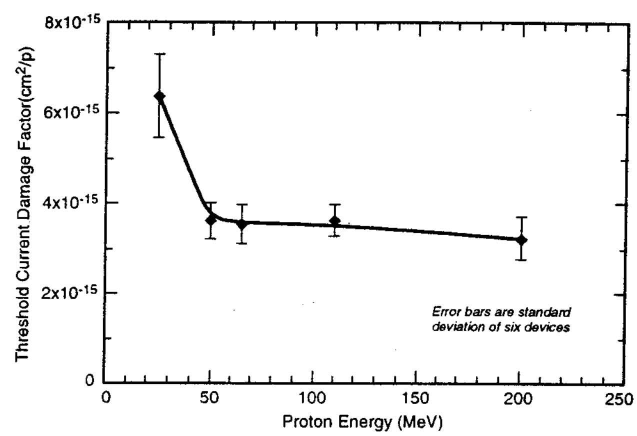

Figure 4. Energy dependence of the threshold current damage factor of the Honeywell VCSEL.

Unlike conventional laser diodes, VCSELs often exhibit steps and nonlinearities in the transfer characterstics (dependence of optical power on drive current). This introduces some uncertainty in defining threshold current, increasing the unit-to-unit variability compared to the other three device types used in the study. Some of the VCSELs also have a gradual transition near the threshold region., adding to the difficulty of defining the threshold current. For these devices, a linear fit was used in the region near the threshold region, extrapolating the fit to determine threshold current.

The damage factor of the VCSELs in our study are similar to those reported by Barnes, et al. in previous work that used 200 MeV protons [13]. They used prototype devices fabricated at Sandia National Laboratories in their study. The wavelength of their devices was the same (850 nm).

B. Annealing

Light-Emitting Diodes

Double-heterojunction LEDs anneal only slightly after irradiation [6,16], resulting in an uncertainty of only a few percent in post-irradiation measurements. However, annealing in other types of LEDs can cause large post-irradiation changes.

Annealing of amphoterically dopes devices has been shown to depend on charge [16]. The rated maximum current can be used as an approximate measure of the current density in order to make comparisons of different device types. For LEDs with 100 mA maximum current ratings annealing begins to become important for injected charge levels of about 0.01 C, and about half the unstable fraction of the damage has annealed with an injected charge of 50 C when 50 MeV protons are used [16].

In the current study we investigated annealing in OP130 amphoterically doped LEDs when they were irradiated at different energies. Figure 5 shows how the annealing progressed with a continuous operating current of 10 mA (10% of the maximum current rating). Damage in the device that was irradiated at 25 MeV began to anneal after much shorter time intervals compared to the device that was irradiated at 200 MeV. Note also that a larger fraction of the damage that was initially produced after irradiation recovered for the device irradiated at 25 MeV compared to the device that was irradiated with 200 MeV protons.

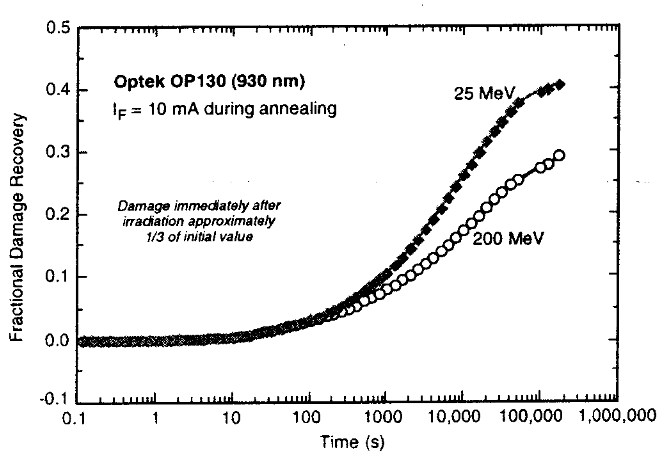

Figure 5. Annealing of the OP130 amphoterically doped LED for devices irradiated at two different energies and annealed with I_F = 10 mA.

Annealing is important for several reasons. First, it can be considered an interference from the standpoint of obtaining consistent measurements of post-radiation damage. Interference from annealing effects can be avoided if measurements are restricted to short time intervals. However, lengthy measurements -- particularly measurements of wavelength with a spectrometer -- can introduce significant errors in damage characterization. Second, annealing is very important for applications because a significant fraction of the post-radiation damage will recover if the device is placed in a forward-biased condition after irradiation.

Laser Diodes

Laser diodes are extremely sensitive to recombination-enhanced annealing. We compared annealing in several of the 650 nm laser diodes using different currents that were applied after irradiation. A constant current was applied to these devices, which were mounted in a temperature-controlled test fixture. Measurements of threshold current were made at periodic intervals, interrupting the annealing sequence temporarily. Figure 6 shows how the threshold current recovered at various currents. The 5 mA and 22 mA conditions were low enough so that the lasers remained below the lasing threshold throughout the annealing period. The fractional recovery in threshold voltage scales with the injection level for those two cases.

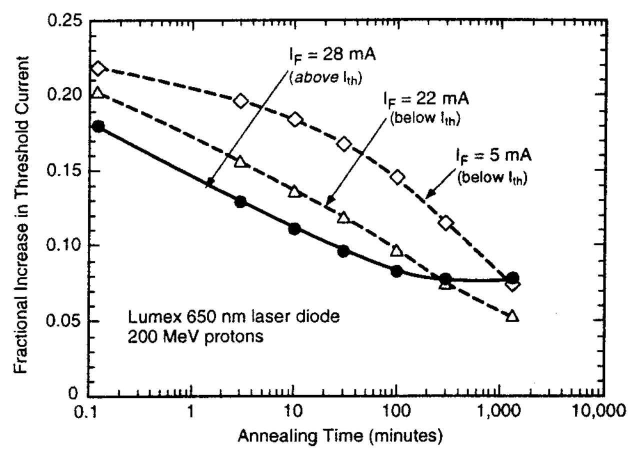

Figure 6. Annealing of the Lumex 650 nm laser diode under different current conditions.

The third condition, 28 mA, was below the post-irradiation threshold current just after irradiation, but eventually exceeded the laser threshold as the annealing progressed. For that case the optical carrier density suddenly increases by several orders of magnitude after the threshold current recovers to 28 mA. Note how much more rapidly the threshold current recovers at 28 mA after approximately 30 minutes of charge injection. This shows that the optical carrier density also affects the rate of annealing in laser diodes in addition to the injected carrier density.

The VCSEL devices were also strongly sensitive to recombination-enhanced annealing. Figure 7 shows how damage in the VCSELs annealed for a representative device with different forward bias conditions during annealing. When the forward current is above the laser threshold about 2/3 of the damage -- as indicated by the fractional increase in threshold current -- recovers in approximately 3 minutes.

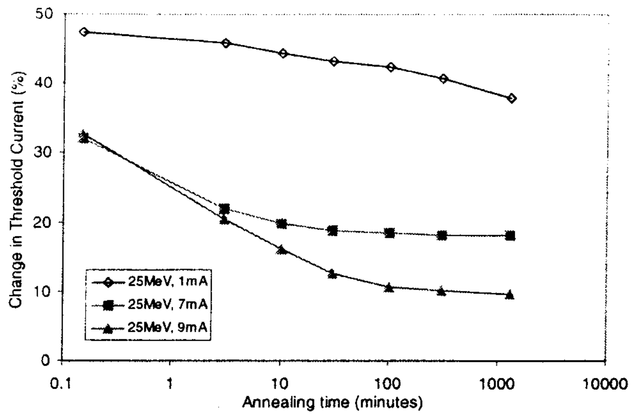

Figure 7. Annealing of the VCSEL laser diodes under different injection conditions.

The recovery period is extended approximately one order of magnitude when the current is somewhat below the post-irradiation threshold current, as shown by the data with $I_F = 7$ mA. Note however that after about 10 minutes the threshold current has decreased to the point where 7 mA is above the laser threshold, so that the 7 mA data corresponds to two different regions: an initial region where I_F is too low for lasing to occur, and a later region where I_F is above the threshold current. The solid and open points in Figure 8 show these differences. Note further that there is an increase in the slope after the device begins to lase with the 7 mA current condition.

For $I_F = 1$ mA the forward current is always below the lasing threshold. Note how little of the damage recovers with this condition, even after extremely long time periods. Because the recovery is so strongly dependent on operating conditions it is possible that some of the recovery with $I_F = 1$ mA may actually be due to the measurements that are made in between the annealing steps.

IV. Discussion

The earlier studies that have attempted to normalize damage using non-ionizing energy loss have mainly concentrated on the energy deposition process. Relatively little attention has been given to damage stability and annealing after irradiation, and those factors can have a large influence on key parameters after irradiation.

Damage stability appears to be different for laser diodes that are subjected to neutron irradiation because the damage sites tend to be dominated by cascades, which partially recover after irradiation even without bias. Several workers, including recent work by Gill, et al. on advanced lasers, have noted that neutron damage anneals significantly even at room temperature [17]. For proton damage, very little annealing occurs without charge injection, but the annealing progresses so rapidly that about 1/3 of the damage recovers within one minute of operation when the device is under forward bias. The stability of unbiased laser diodes is illustrated in the data of Figure 8. In this figure, four different laser diodes were placed in the same test fixture and tested periodically over a time interval of about one month. The temperature was held constant at 25 °C. One of the devices was unbiased, while the other three were biased at different currents. The lowest current (shown by the open symbols) was below the lasing threshold of the device. Note that the unbiased device exhibited no recovery during this extended time interval, but that about 20% of the damage will recover during the first two minutes of operation when the device is functioning as a laser.

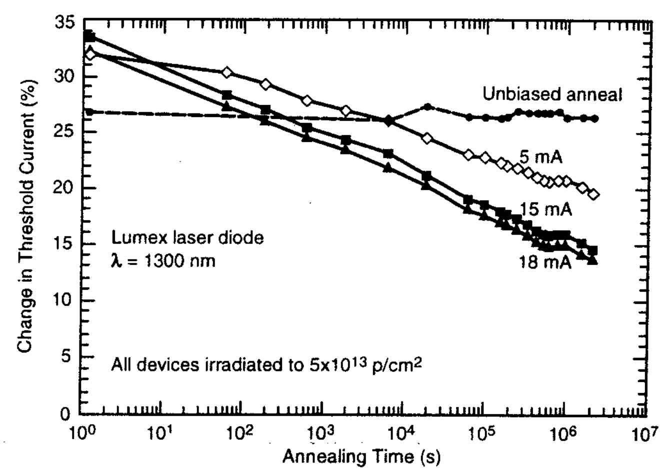

Figure 8. Annealing of laser diodes under various bias conditions.

Laser diodes appear to have the same flat dependence of damage on energy shown by double-heterojunction LEDs, and they clearly do not show the increase in damage at higher energies that is predicted by theoretical calculations of NIEL. This result is quite different from the earlier results reported by Lee, et al.[5]; however, their results were somewhat inconsistent between different units, making it difficult to reach a definite conclusion about energy dependence with the small number of samples used in their study.

The energy dependence of double-heterojunction LEDs appears to be very similar to that of the laser diodes, but LEDs with double-heterojunction construction do not show the extreme sensitivity to annealing exhibited by laser diodes. This may be caused by the fundamental difference in operation between the two types of devices: laser threshold current depends nonlinearly on non-radiative recombination sites within the laser path, whereas the presence of similar defects in an LED mainly affect the light output at low current, below the range of normal operation.

Proton damage in amphoterically doped LEDs has a markedly different energy dependence. Amphoterically doped LEDs require very long minority carrier lifetime because of the extended graded region between the n- and p-type layers that form the LED. Damage in amphoterically doped LEDs is strongly affected by annealing.

The extreme sensitivity of LEDs and laser diodes to recombination-enhanced annealing is extremely important not only in characterizing device behavior, where it can act as an interference, but also in interpreting radiation damage for system applications. For steady state (or high duty cycle applications), annealing will reduce the effective amount of damage that occurs. However, in low duty cycle or pulsed applications, very little annealing will occur and there is far more damage compared to steady state applications. The observation that annealing is somewhat different for low and high energy protons has to be taken into account when radiation test results are interpreted for system use.

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